Development of Electrostatically Enhanced Core Separator for Particulate Air Toxics Control

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Introduction

The Clean Air Act Amendments of 1990 have identified 189 chemical elements and compounds as hazardous air pollutants (HAPs). The U.S. Environmental Protection Agency (EPA) has been given the task of evaluating the health risks of these so-called air toxics and determining their acceptable emission rates. The U.S. Department of Energy (DOE), in cooperation with private industry, is sponsoring research into developing new air toxic emission control technologies.

Coal typically contains trace amounts of HAPs, the species and amounts vary with coal type and source. Combustion of coal in Fossil Energy Power Systems releases these HAPs into the combustion gas where they flow to the stack by passing through the gas cleanup system. Except for mercury and selenium, the HAPs exist primarily in the solid phase temperatures typical of flue gases so they can be removed by particulate cleanup systems. In fact, these solid phase HAPs are removed with approximately the same efficiency as the other particulate matter. Table 1 shows the removal efficiency of 15 HAPs by an electrostatic precipitator having an efficiency of approximately 99 percent.

These results suggest that very high removal efficiencies of particulate HAPs can be achieved by using a very high efficiency particulate collector. Epidemiological studies[1] suggest that there may be health benefits from reducing concentrations of particulate matter in the ambient air. This paper will discuss the development of a very high efficiency particulate collector called the Electrostatically Enhanced Core Separator (EECS) system that may have the potential to significantly reduce the emission rates of both particulates and particulate air toxics from Fossil Energy Power Systems.

Table 1: Hazardous Air Pollutant Removal Efficiency of an Electrostatic Precipitator[2]

Element	*Symbol*	*Removal Efficiency [percent]*	*Element*	*Symbol*	*Removal Efficiency [percent]*
Antimony	Sb	81.00	Copper	Cu	99.60
Arsenic	As	99.10	Manganese	Mn	99.60
Barium	Ba	99.80	Mercury	Hg	<20.00
Beryllium	Be	97.40	Molybdenum	Mo	96.00
Cadmium	Cd	99.20	Nickel	Ni	98.20
Chromium	Cr	99.20	Phosphorus	P	98.00
Cobalt	Co	99.30	Vanadium	V	99.50

Approach

The Electrostatically Enhanced Core Separator (EECS) system is derived from LSR's Core Separator technology that was developed as a mechanical particle collector. The mechanical system consists of a cyclone, recirculation fan and a particle separator called the Core Separator. The Core Separator is a cylindrical centrifugal separator. The gas with entrained particles enters the cylinder through a tangential slot. The tangential inlet induces a spinning motion to the gas that causes the entrained particles to migrate toward the outer wall. The clean gas is removed axially from the center of the cylinder and the particles, along with some bleed flow, are extracted through a second tangential slot. The bleed flow with the entrained particles is directed to the cyclone then through the recirculation fan back to the Core Separator inlet. In this configuration, the system collection efficiency is a function of both the Core Separator efficiency and the cyclone efficiency as shown in Equation 1. The important feature of Equation 1 is that the system efficiency is primarily governed by the efficiency of the Core Separator. For example, if the Core Separator efficiency is 99.9 percent and the cyclone efficiency is only 30 percent, the system efficiency is still 99.67 percent.

$$\eta_{sys} = \frac{\eta_{cs}\ \eta_{cyc}}{1-\eta_{cs}(1-\eta_{cyc})} \qquad \text{Equation 1}$$

Where

η_{sys} *Core Separator* system collection efficiency

η_{cs} *Core Separator* separation efficiency

η_{cyc} cyclone collection efficiency

What is happening physically is that, while the process flow passes through the separator once and leaves the system, the particles keep recirculating through the cyclone until they are eventually collected. To particles, this system appears to a large number of cyclones in series. That is why the system efficiency can be significantly higher than the efficiency of the cyclone alone.

Due to the nature of turbulent two-phase flows, it is much easier to design a high efficiency separator than a high efficiency collector. Cyclones suffer from trying to satisfy two conflicting requirements. They need high inlet velocities to bring the entrained particles to the walls and they need low velocities to ensure that the separated particles flow down the walls into the hopper without being reentrained into the swirling flow. In the Core Separator we do not collect the particles so we can use high velocities to achieve very high separation efficiencies without having to worry about reentrainment.

We employ basically the same idea in the EECS system as in the Core Separator system except that the components are configured in a collector-first orientation, a particle precharger is added upstream of the separator, and electrostatic field is applied to the Core Separator to improve its performance with sub-micron sized particles. The efficiency of the collector-first orientation is given by Equation 2.

$$\eta_{sys} = \frac{\eta_{col}}{1-\eta_{EECS}(1-\eta_{col})} \qquad \text{Equation 2}$$

Where

η_{sys} EECS system collection efficiency

η_{EECS} EECS separation efficiency

η_{col} Efficiency of particle collector

In the collector-first arrangement, if the EECS has an efficiency of 99.9 percent and the collector has and efficiency of 30 percent then the system efficiency is still 99.77 percent. Because the EECS system requires a separate collector, it is ideally suited for retrofit applications where the existing electrostatic precipitator (ESP) can be used as the collector. Since the EECS system performance is relatively independent of the collector performance, almost any ESP, no matter how poorly it operates, can be successfully retrofitted by the addition of an EECS. In fact, it may be possible to remove the last section of the ESP, place the EECS inside the existing housing and still achieve very high particle collection efficiencies with no increase in the size of the ESP footprint.

What physically happens in the EECS system is that particles that make it through the ESP on their first pass are separated from the exhaust gas and returned to the ESP inlet for a second pass. For these particles, the ESP appears to have an SCA twice what the original ESP had. If any particles make it through on the second pass, they are directed back to the inlet for a third. If the EECS had a separation efficiency of 100 percent, no particles could escape with the exhaust gas and the system efficiency would be 100 percent as shown by Equation 2. To recirculating particles, the system appears to have infinite SCA which is what the Andersen-Deutch equation indicates is required for 100 percent collection efficiency.

Of the three components that make up the EECS system, the EECS, the ESP and the recirculation fan, the focus of this Phase I research program has been on the development of a high efficiency EECS that is compact, has low capital cost and operates with low pressure drop. The next section describes that development process.

Project Description

The task of developing the EECS involved taking the basic Core Separator geometry, adding an axial discharge electrode and determining which flow regimes produced the best performance. This was done in two steps. Some geometry changes were made in the second EECS directed toward improving the electrical characteristics and reducing manufacturing costs in a full scale system.

Laboratory tests were conducted using a simulated exhaust stream created by disbursing fly ash from Public Service of Colorado's Comanche Station into the exhaust gas from a natural gas burner. Comanche Station burns pulverized western subbituminous coal in a subcritical boiler and the fly ash is collected in a baghouse and shipped to LSR in 55 gallon drums. A measured amount of ash is disbursed through an air ejector into the EECS inlet duct and the concentration of dust was measured in the EECS clean flow outlet using a simplified EPA Method 5 sampling procedure. The calculated efficiency was then determined using Equation 3.

$$\eta_{EECS} = 1 - \frac{C_{out}\, V_{avg}\, A_{duct}\, \tau}{m_{in}} \qquad \text{Equation 3}$$

Where

η_{EECS}	EECS separation efficiency
C_{out}	Mass concentration of particulate matter in the EECS clean flow outlet as determined by EPA Method 5
V_{avg}	Average gas velocity in the EECS clean flow outlet duct
A_{duct}	Cross-sectional area of the EECS clean flow outlet duct
τ	Test duration
m	Mass of particulate matter introduced at the EECS inlet

In addition to the efficiency, the EECS gas inlet velocity and bleed flow were measured so that the EECS efficiency could be plotted against these two flow variables. Also, the particle size distribution was measured at the inlet and clean flow outlet order to determine the EECS partial separation efficiency.

While the first EECS tested had a design flow rate of 950 m^3/hr (560 acfm) with a length to diameter ratio of about 2.5 to 1, the second unit, shown in Figure 3 and Figure 4, had a design flow rate of 2850 m^3/hr (1680 acfm) with a length to diameter ratio of about 7.5 to 1. All the interior edges of the second EECS were rounded or fitted with corona shields to allow higher field strengths before the onset of sparking. Also, the longer length means that, for a given gas flow rate, fewer EECS subassemblies would be required thereby reducing the capital cost. Tests of this geometry showed the cost savings could be achieved without paying a performance penalty.

After completion of the laboratory tests, the EECS unit was shipped to Alabama and installed at Alabama Power Company's James H. Miller, Jr. Electric Generating Plant in Quinton, Alabama. The unit was tested in an exhaust gas slipstream from Unit No. 3 burning a sub-bituminous coal from the Powder River Basin. The EECS was installed downstream of the COHPAC II unit[3] which was operated with its filter bags removed. By reducing the output voltage of COHPAC unit's high voltage power supplies, we were able to control the EECS particulate inlet loading and thereby simulate the inlet loading coming from a range of under-performing ESPs.

The final Phase I task was to produce an updated cost estimate of an EECS retrofit based on a 250 MWe plant. The cost estimate was performed by Sargent and Lundy, LLC as part of a subcontract. LSR provided them with a conceptual design based on the results of the EECS testing.

Results

Laboratory Tests

Most of the EECS testing was done at ambient temperature. Due to the simplicity of conducting ambient temperature tests, it made the process of identifying the most interesting operating regimes much quicker. Once the ambient temperature performance map was created, a series of high temperature tests was conducted to determine the effects of elevated temperature.

The results showed an efficiency high of over 99 percent. They also show a trend of decreasing efficiency with increasing inlet velocity, a trend typical of conventional ESPs. In the mechanical Core Separator the efficiency increased with increasing inlet velocity due to the higher centripetal forces generated so it appears that in the EECS the electrical forces are dominant in the separation process. The EECS is indeed performing as an electrostatic separator, not a mechanical one.

Using Equation 3, it is possible to estimate the efficiency of a complete EECS system by assuming an efficiency for the ESP collector. For an ESP having a collection efficiency of 97 percent, the estimated system efficiency varies from 99.84 to 99.97 percent. It should be pointed out that these are only rough estimates of the system efficiency. A more systematic approach is to use an assumed system inlet size distribution, a partial collection efficiency for the ESP and the partial separation efficiency for the EECS. Even this more involved procedure still provides only an approximate result because it does not include the performance coupling effect due to particle agglomeration and attrition.

Field Test Results

Six EECS efficiency tests were conducted at Alabama Power Company's Plant Miller. The tests were conducted with two EPA Method 5 gas sampling trains to measure the EECS inlet and EECS clean flow outlet particulate concentrations. The EECS was operated at a nominal specific collecting area of 19.7 $m^2/(m^3/s)$ (100 ft^2/kacfm) The first test was conducted with no electric power applied to the EECS to get a baseline performance of the mechanical separator. The measured efficiency was 44.5 percent. The results of the final four tests with the precharger operating normally are shown it Figure 1 in S.I. units and in Figure 2 in English units. The efficiencies of these runs are between 86 and 96 percent. The data show that the EECS is capable of reducing the emissions from under-performing ESPs having outlet loadings as high as 280 ng/J (0.65 lbm/million Btu) down to below

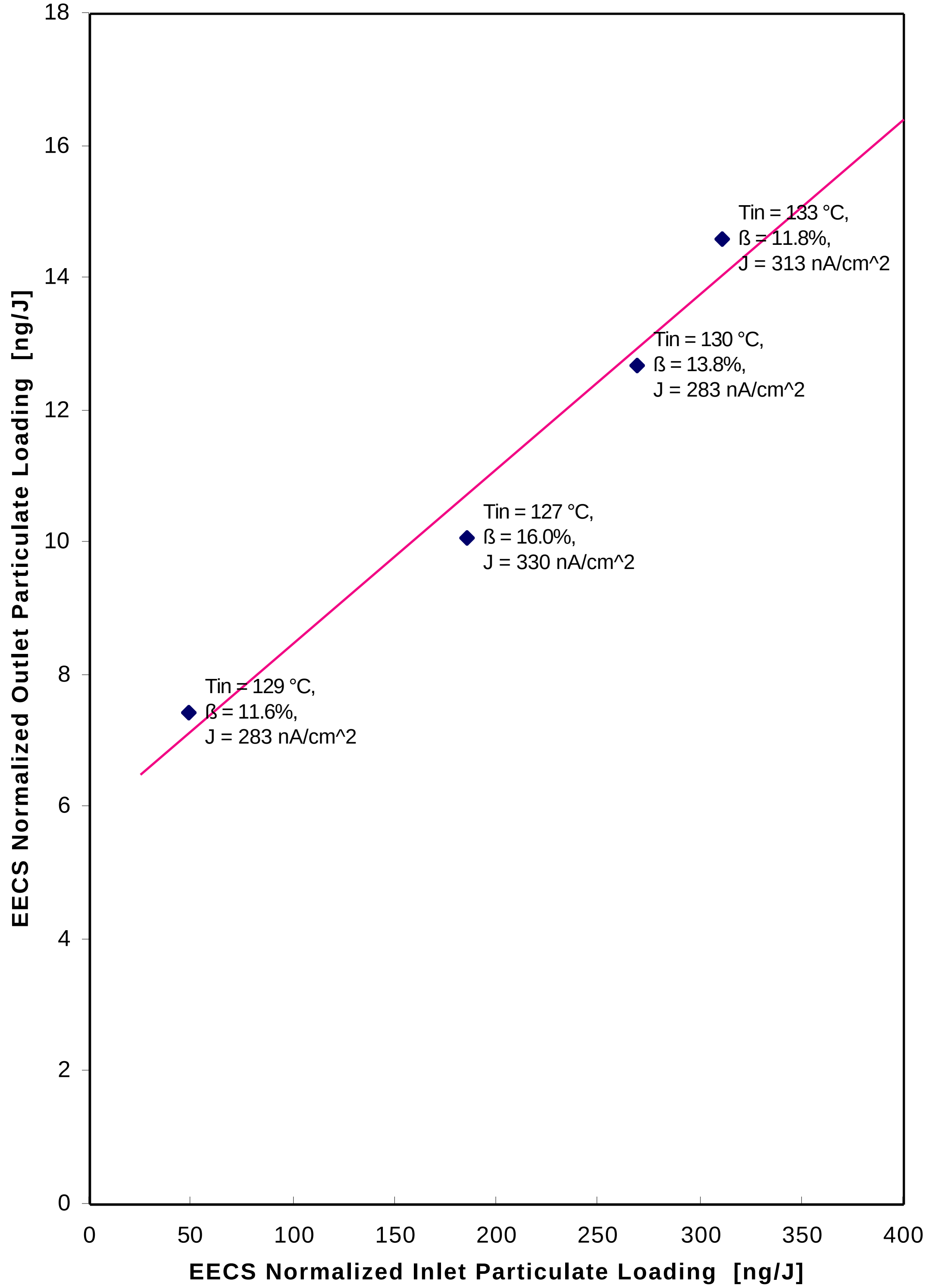

Figure 1: EECS Field Test Results, S.I. Units

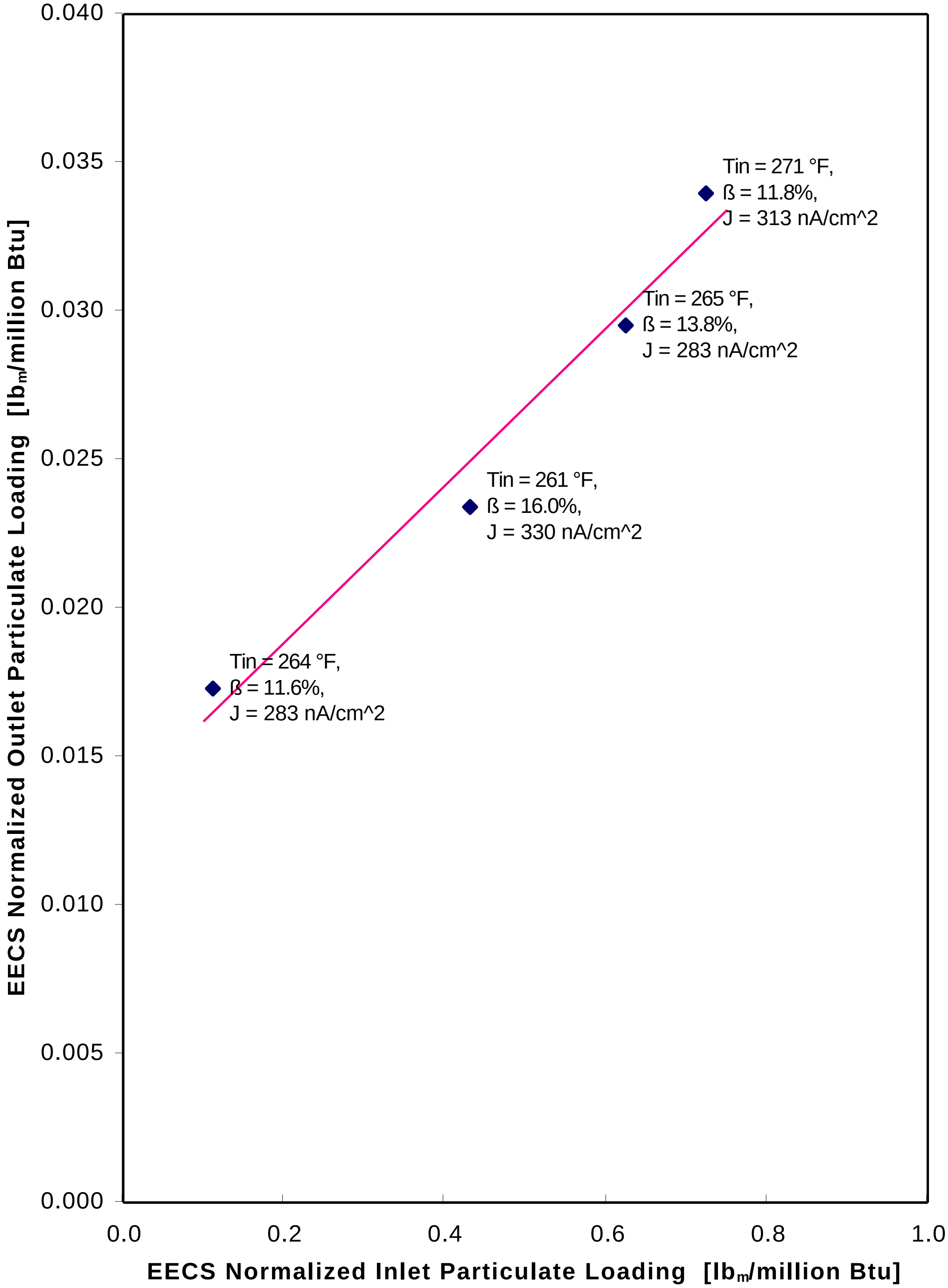

Figure 2: EECS Field Test Results, English Units

13 ng/J (0.03 lbm/million Btu). All runs had a pressure drop of less than 100 pa (0.4 in wc) and during the approximately two weeks of operation the prechargers were cleaned once with a compressed air lance while the EECS itself was not cleaned at all.

Application

The most immediate application of the EECS system will be to provide a retrofit system for coal-fired power plants currently operating under-performing ESPs. According to a cost study performed by Sargent and Lundy, LLC in 1994, the capital cost for a retrofit EECS is about $8 million for a 250 MW plant including a 40 percent process contingency.[4] This is approximately the same capital cost as EPRI's COHPAC concept where a high air-to-cloth ratio baghouse is placed downstream of an under-performing ESP. Toward the end of this project Sargent and Lundy, LLC will re-evaluate the EECS costs taking into account the design modifications and operating experience gained from the field tests conducted at Alabama Power Company's Miller Steam Plant.

The second application of the EECS system is to retrofit ESPs that currently meet particulate emission requirements but may not meet the species-specific air toxic emission regulations that are expected from EPA in the near future. The development of EECS concept will proceed with the immediate needs of the first group in mind and will be ready for the second group if the if the EPA air toxic emissions rules should require it.

The final task of this Phase I project was an economic analysis performed by Sargent and Lundy, LLC. In 1994 Sargent and Lundy performed an economic analysis showing the EECS to have a capital cost of about $8 million for a 250 MWe plant. This cost estimate included a 40 percent process contingency due to its immature stage of development at the time of the analysis. The new analysis showed a decrease in the capital cost due primarily to the fact that, with a pressure drop of only 100 pa (0.4 in wc) the forced draft fans will not need to be modified. An additional reduction is due to lower contingencies now that the technology has been demonstrated in the field.

Future Activities

In Phase II, a 34000 m^3/hr (20000 acfm) EECS module will be constructed and tested for particle separation efficiency and for separation efficiency of 16 HAPs. Activated carbon sorbent will be injection upstream of the EECS to measure the separation efficiency of gas phase air toxics such as mercury. The second phase will also include testing of the first wet EECS element. As in Phase I, the final task of phase II will be a detailed economic assessment of the EECS system to be performed by Sargent and Lundy.

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Figure 3: EECS Showing Clean Flow Outlet

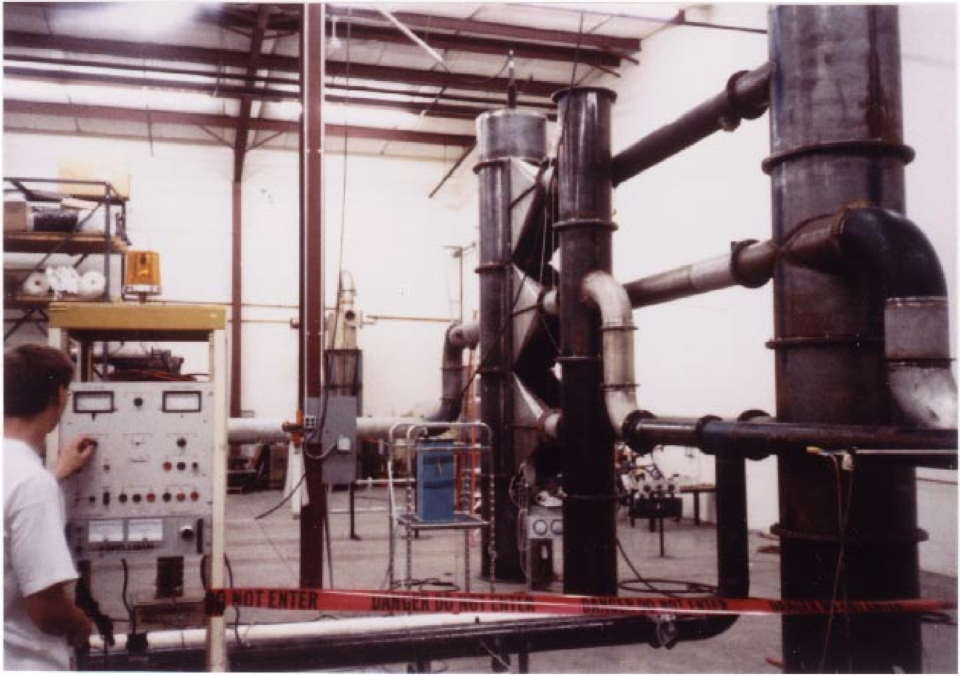

Figure 4: EECS Showing Precharger and Bleed Flow Outlet

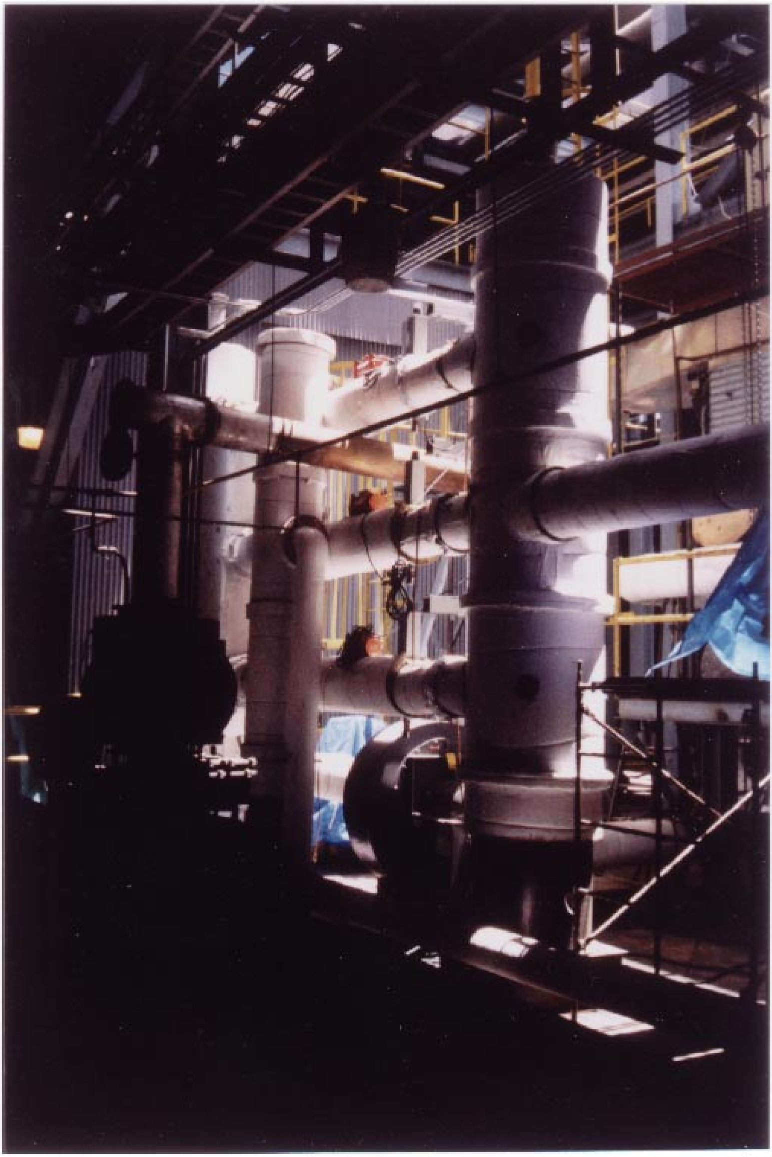

Figure 5: EECS at Plant Miller